51 Control Systems and Automation in Steel Thixoforming Production

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INTRODUCTION

The products manufacturing such as thixoforming involves a long line of complex steps: Ingots elaboration, shearing and sawing, transfer, reheating, second transfer to the press, transformation by forming process, extraction of the produced part and its transfer to heat treatment, and finally cleaning and lubricating the forming dies. This processing is given in Figure 51.1 where the process used to obtain the thixoforming steel bars is a classical steel elaboration with continuous casting or ingots and hot rolled operations to obtain the good diameter and the manufacturing line is equivalent to the hot forging fabrication process.

The slug transfer between the heating zone and the press and to the posttreatment zone is automated and may be realized with handling systems or with robots, with the latter being fast and accurate.

Process control aims at improving global productivity and quality of the resulting products by optimizing each elementary step.

PROBLEM DEFINITION

Complex processes, involving generally many variables, require for their control more or less sophisticated models. These process models are either analytical when physical and thermodynamic mechanisms are known, or statistical or knowledge based, according to circumstances. It is necessary to have reliable and precise models to adjust undetermined parameters during process development and to be able to take into account external parameters variability during the process. These models concern both running of machines and testing of manufactured parts under the process conditions: temperature, speed, forming load, etc.

In this context, in-line nondestructive testing methods contribute efficiently because they may give directly and in real-time products characteristics and process needs.

In such cases of thixoforming, the sine qua none condition to have a reliable process is the temperature control during the reheating of the slugs, which determines the desired liquid fraction. The produced part quality is linked to this liquid fraction (LF) either in terms of its amount or in its distribution in the slug. The amount of liquid fraction has an impact on the part complexity. Higher the LF complex more uniform is its distribution and better is its quality.

Figure 51.2 gives the liquid fraction versus the temperature plot for low carbon steel [1]. To obtain an ideal proportion of liquid phase in the slug, between 20% and 50%, it is necessary to adapt the heating conditions in order to have good proportion between liquid and solid fraction and the best homogeneity in all the slug volume. The heating cycle must also be adapted for obtaining the primary globular structure at the thixoforming temperature. Generally, the steel grades are determined at the thixoforming process.

Inductive reheating of billets is the state-of-the-art method to get the desired liquid fraction of the microstructure of a steel billet for thixoforming. In laboratory experiments, temperature might be directly controlled since it is usually possible to apply thermocouples for temperature measurements. Due to technical restrictions, temperature measurements especially in the interior of a billet are difficult in industrial heating processes. For this reason, thixoforming billets are heated without temperature monitoring by using proven heating functions. Such functions are usually obtained by trial-and-error or on the basis of finite element (FE) simulations. In both cases, exhaustive experimental work is usually necessary. Moreover, FE simulations require thermophysical material data that could be difficult to obtain for industrial relevant heating processes.

This chapter gives two representative examples of improvement of the accuracy of an in-line measurement and controlling of the liquid fraction during the reheating step of the thixoforming process. Finally, the last section is dedicated to the automation of the thixoforming processes.

THERMOPHYSICAL PROPERTIES AND ENERGY-BASED CONTROL

For liquid fraction controlling, the first possibility is the determination of the amount of energy supplied by the heating converter and coupled into the piece (initially cold) until the desired liquid/solid fraction has been reached.

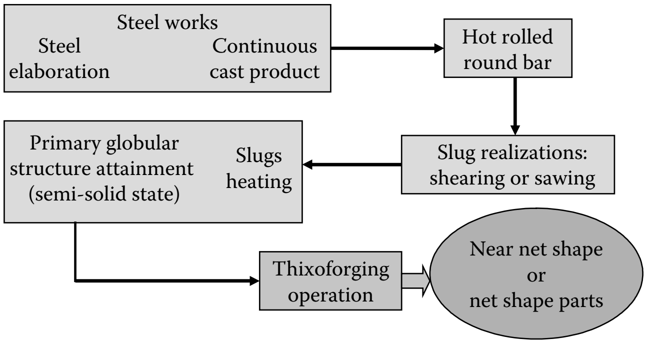

Steel works
Steel elaboration
Continuous cast product
Hot rolled round bar
Slug realizations: shearing or sawing
Slugs heating
Primary globular structure attainment (semi-solid state)
Thixoforging operation
Near net shape or net shape parts

FIG. 51.1
Thixoforming processing of steels.

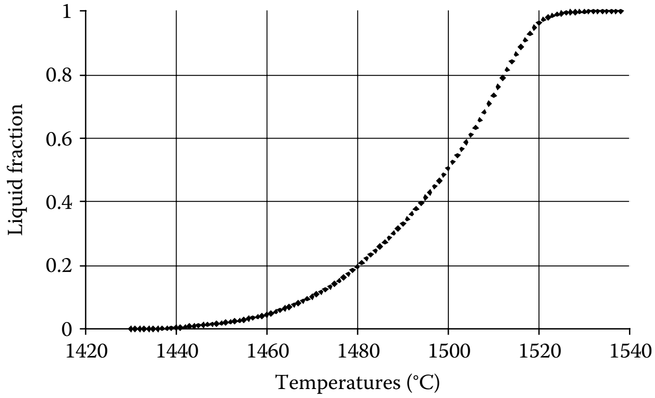


FIG. 51.2
Evolution of the liquid fraction versus the temperature for carbon steels.

If the energy losses in the electrical circuit, and by mainly the radiation from the hot piece during the whole heating process, are constant in the repetitions of a defined process. The amount of energy required to heat up the billets that are made up from the same material (steel in this case) having the same size will be constant.

The problem is to find the relationship between the amount of energy supplied by the converter, the energy consumed by the billet and, consequently, the reached liquid/solid fraction in the billet. The consumed energy in the billet at the end of the heating process depends strongly on the radiation losses from the surface of the piece, which depend on the cycle (how long the piece stays at high temperatures), thermal insulation, and the temperature of insulating material around the billet.

As shown in Figure 51.3, this model is able to estimate the energy in the piece during a certain heating process only on the basis of electrical parameters (voltage, current, power, frequency), heating cycle (pulses and pauses), material properties (geometrical shape, electrical and thermal conductivity, specific heat as functions of temperature), and energy losses in the electrical equipment and from the piece. After validation with known processes, the model also works with the new cycles without direct measurements on the hot billet.

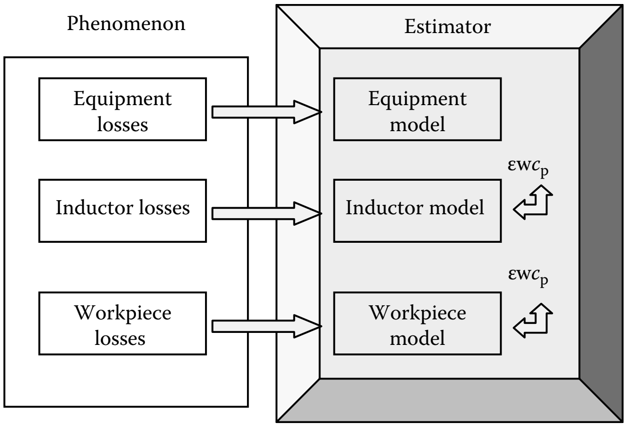


FIG. 51.3
Link between physical phenomenon and estimator model.

This model evaluates the energy stored in the piece (enthalpy) as a function of electrical parameters and material properties. The system, which consists of continuous parameters, has been simulated by a concentrated parameters model with an adequate number of states using MATLAB® and SIMULINK®. It works by electrothermal equivalence and needs the exact knowledge of physical properties of the material. The results given by the model have been compared with the experimental tests to validate the model.

The performed tests confirm that the amount of energy supplied during a given heating cycle is constant, but if the cycle changes, there is also a change in the total amount of energy that must be supplied to obtain the same physical status (liquid/solid fraction).

The estimator receives as input the electrical parameters of the power supply (voltage, current, power, and frequency) and the current value of the billet surface temperature (measured by a pyrometer assuming uniformity on the whole piece). It analyzes this information, puts it together with the data from the model, and calculates the resulting status of the billet.

BILLET MODEL DESIGN AND DEVELOPMENT

The billet is assumed to be constituted by a certain number *n* of layers; an electric pseudolinear model is determined, in which each node corresponds to a layer.

The devised model is called pseudolinear, since it maintains the structure of a linear system, but constrains and nonlinearities in the parameters, that is, the parameters of the model are functions of the state of the system itself. The notation is set as follows:

- n number of nodes (layers) considered in the model
- P_{in} thermal power heating the billet
- P_{el} electrical power in the inductor
- P_{L} thermal power lost from the surface of the billet (due to radiation)

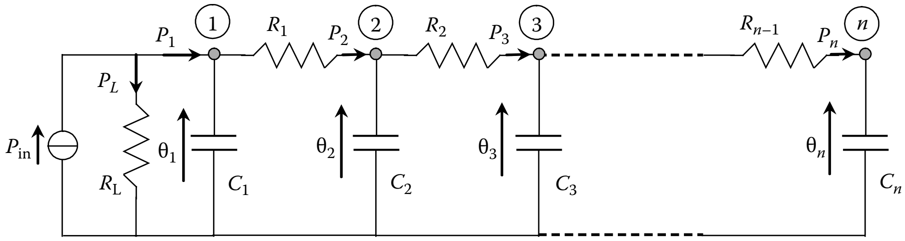


FIG. 51.4
The electrical equivalent of the model.

- P_i thermal power entering node i
- η efficiency of the inductive heating system (we assume $P_{in} = \eta P_{el}$)
- η_i temperature of the ith node
- R_L equivalent radiating loss resistance
- R_i thermal resistance from node i to node $i+1$
- C_i thermal capacity of node i

The electrical equivalent of the model with n nodes is depicted in the Figure 51.4.

The equilibrium equations for the first node are

$$P_1 = P_{in} - \frac{\theta_1}{R_L}, \quad P_2 = \frac{\theta_1 - \theta_2}{R_1} \tag{51.1}$$

$$\dot{\theta}_1 = \frac{P_1 - P_2}{C_1} = \frac{1}{C_1}\left[P_{in} - \left(\frac{1}{R_L} + \frac{1}{R_1}\right)\theta_1 + \frac{1}{R_1}\theta_2\right] \tag{51.2}$$

For the generic ith node ($i=2,\ldots, n-1$), the equation can be written as

$$P_i = \frac{\theta_{i-1} - \theta_i}{R_{i-1}}, \quad P_i - P_{i+1} = \frac{1}{R_{i-1}}\theta_{i-1} - \left(\frac{1}{R_{i-1}} + \frac{1}{R_i}\right)\theta_1 + \frac{1}{R_i}\theta_{i+1}$$

which yields to

$$\dot{\theta}_i = \frac{P_i - P_{i+1}}{C_i} = \frac{1}{C_i}\left[\frac{1}{R_{i-1}}\theta_{i-1} - \left(\frac{1}{R_{i-1}} + \frac{1}{R_i}\right)\theta_1 + \frac{1}{R_i}\theta_{i+1}\right] \tag{51.3}$$

For the nth node, it is: $P_n = (\theta_{n-1} - \theta_n)/R_{n-1}$, $P_{n+1} = 0$, therefore $\dot{\theta}_n = (\theta_{n-1} - \theta_n)/R_{n-1}\, C_n$.

As already mentioned, the model is pseudolinear, since the parameters are not constant, but they depend on the value of the node temperatures θ_i. However, the system equations in the standard state-space form can be formally written in the standard state-space form, assuming the state vector to be $\theta = [\theta_1 \cdots \theta_n]$ and the parameters are dependent on the states, that is, $C_i = C_i(\Theta)$, $R_i = R_i(\Theta)$.

For the particular case of $n=3$, the system equations in matrix form are as follows:

$$\dot{\theta} = \begin{bmatrix} -\frac{1}{R_{L1}C_1} & \frac{1}{R_1C_1} & 0 \\ \frac{1}{R_1C_2} & -\frac{1}{R_{12}C_2} & \frac{1}{R_2C_2} \\ 0 & \frac{1}{R_2C_3} & -\frac{1}{R_2C_3} \end{bmatrix}\theta + \begin{bmatrix} \eta/C_1 \\ 0 \\ 0 \end{bmatrix} P_{in} \tag{51.4}$$

where
R_{L1} is defined as the parallel of R_L and R_1
R_{12} as the parallel of R_1 and R_2

For $n=4$, the system equations in matrix form are as follows:

$$\dot{\theta} = \begin{bmatrix} -\frac{1}{R_{L1}C_1} & \frac{1}{R_1C_1} & 0 & 0 \\ \frac{1}{R_1C_2} & -\frac{1}{R_{12}C_2} & \frac{1}{R_2C_2} & 0 \\ 0 & \frac{1}{R_2C_2} & -\frac{1}{R_{23}C_3} & \frac{1}{R_3C_3} \\ 0 & 0 & \frac{1}{R_3C_4} & -\frac{1}{R_3C_4} \end{bmatrix}\theta + \begin{bmatrix} \eta/C_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} P_{in} \tag{51.5}$$

where R_{23} denotes the parallel of R_2 and R_3.

In general, the model is written in the form

$$\dot{\theta}(t) = A(\theta)\theta(t) + B(\theta)P_{in}(t) \tag{51.6}$$

where
A is an $n \times n$ matrix (whose value depends on the current value of the state)
B is a column vector

System Discretization

For simulation and purposes of further analysis, the above model is discretized using some an appropriate sampling period T. The resulting discrete-time system assumes the form

$$\theta(k+1) = A_d(\theta(k))\theta(k) + B_d(\theta(k))P_{in}(k) \tag{51.7}$$

in which the discretized system matrices are given by

$$A_d(\theta(k)) = e^{A(\theta(k))T}, \quad B_d(\theta(k)) = \int_o^T e^{A(\theta(k))\tau} B(\theta(k))\, d\tau \tag{51.8}$$

Assuming **A** invertible (as it is expected, since the system is passive), the integral above can be simply computed as

$$B_d(\theta(k)) = A^{-1}(e^{A(\theta(k))T} - I)B(\theta(k)) \tag{51.9}$$

Due to the "slow" nature of the dynamics under consideration, it seems reasonable to choose a sampling time of the order of the tenth of second or higher ($T \geq 0.1$ s).

Extraction of Model Parameters from Physical Data

The introduced model parameters, relative to each layer, must be extracted from the available physical data.

Let h and r be the height and the base radium of the billet respectively, separated into n layers, with the layers enumerated starting from the exterior one (i.e., layer l_n is the central one). A sketch of the case of three layers, which will be considered in the simulation tests, is shown in Figure 51.5.

Let the layers be defined so that the following condition holds:

Condition: *The n layers of the billet have the same volume.*

Under the assumption that the mass density of the billet is constant, this condition guarantees that the layers have the same mass.

The base area of each layer is given by

$$S_i = \pi r_i^2 - \pi r_{i+1}^2, \quad i = 1, \ldots, n \tag{51.10}$$

where r_i denotes the exterior radium of each layer starting from the external one, so that $r_1 = r$, and $r_{n+1} = 0$.

Condition holds if the base areas are all equal, that is, if

$$S_i = \frac{\pi r^2}{n} \quad \forall i$$

It follows that the layers radii r_i must satisfy the relation

$$r_{i+1}^2 = r_i^2 - \frac{1}{n} r^2$$

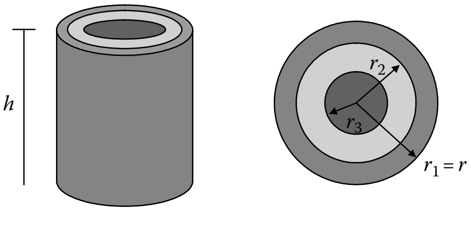


FIG. 51.5
Three layer model of the billet.

In the simulated three-layer case, the radii are then such that

$$r_1^2 = r^2, \quad r_2^2 = \frac{2}{3} r^2, \quad r_3^2 = \frac{1}{3} r^2$$

Each layer has then the same volume, given by

$$V_i = \frac{\pi r^2}{n} h \quad \forall i \tag{51.11}$$

And the same mass given by

$$m_i = \rho V_i \quad \forall i \tag{51.12}$$

where ρ is the mass density (expressed in kg/m^3).

The electric model is characterized by the following parameters:

- The resistance R_L, which takes into account the losses due to thermal radiation
- n capacitance C_i (one per each layer)
- $n - 1$ resistances R_i (one between each couple of layers)

Each parameter is a function of the current temperature value.

The parameter values to be used in the simulation tests are determined starting from the available data sheets [2], with reference to the temperature values at which the data was collected. In particular:

1. The radiation resistance values $R_L(\vartheta)$ at each temperature is given by

$$R_L(\vartheta) = \frac{\vartheta}{P_L} \text{ (K/W)} \tag{51.13}$$

   with P_L as lost power due to thermal radiation at temperature ϑ given by

$$P_L = \varepsilon \times 5.67 \times 10^{-8} \vartheta^4 \times 2\pi r h \text{ (W/m}^2\text{)} \tag{51.14}$$

   (Coefficient ε is assumed to be equal to 0.5 in the simulation tests.)
2. The capacitance value $C_i(\vartheta)$ of the ith layer at temperature ϑ was determined by the thermophysical data for C38 Thixosteel as

$$C_i(\vartheta) = [\text{C35\_RoCp}(\vartheta)]\, V_i \text{ (J/K)} \tag{51.15}$$

3. The resistance value $R_i(\vartheta)$ between the layers i and $i+1$ at temperature ϑ is determined by the thermal conductivity data T_C as

$$R_i(\vartheta) = \frac{1}{[T_C(\vartheta)] l_i}, \quad i = 1, \ldots, n-1 \tag{51.16}$$

with

$$l_i = 0.5(r_i - r_{i+2}), \quad i = 1,\ldots,n-1$$

The available steel data for C38 "Thixosteel" are reported in Figures 51.6 and 51.7.

SIMULATION OF THE HEATING PROCESS

The simulation of the heating process is based on the discrete-time recursion developed above, and is based on three steps:

- Given the current time instant k, the current system state $\Theta(k)$, and the current value of input power $P_{\text{in}}(k)$, compute the values of model parameters using table lookup and interpolation (if needed) from steel manufacturer data.
- Building the matrices $\mathbf{A}(\Theta(k))$, $\mathbf{B}(\Theta(k))$, construct their discrete-time versions $\mathbf{A}_\text{d}(\vartheta(k))$, $\mathbf{B}_\text{d}(\vartheta(k))$.
- Using the discrete-time recursion to update the value of the system state, that is, compute $\Theta(k+1)$.

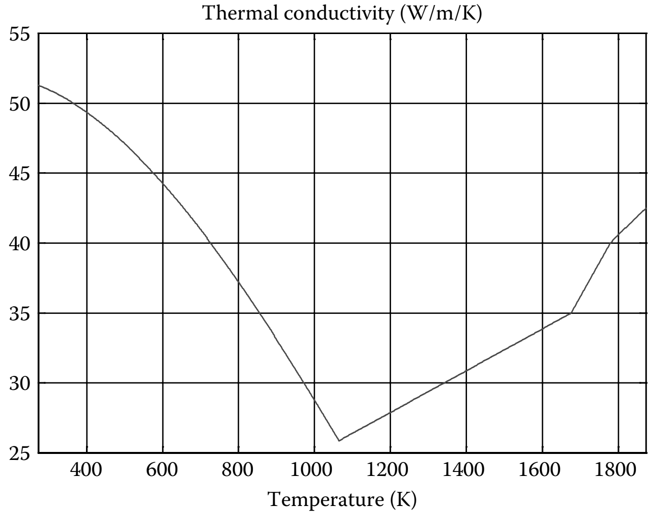


FIG. 51.6
Thermal conductivity of C38 steel.

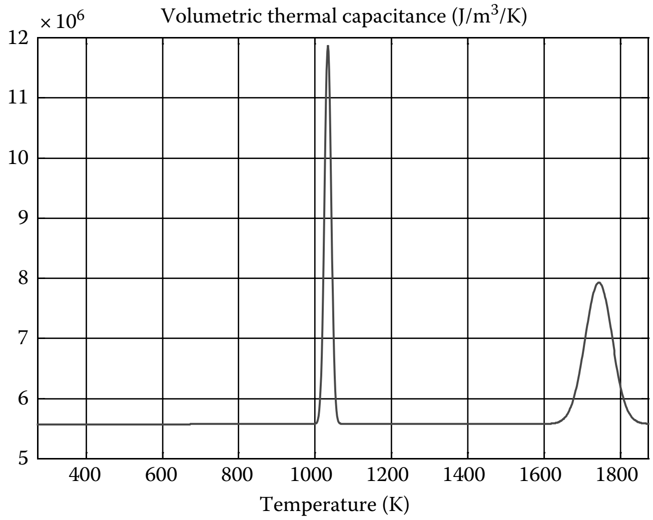


FIG. 51.7
Volumetric thermal capacitance of C38 steel.

Physical Parameters for C38 Steel

In order to work "online" in an industrial loop, the algorithm has been rewritten into a "real-time" version. The complete validation of this new model (real-time version of the algorithm) was done with the new experimental data of C38 steel [2, 3].

The validation of simulation result gives good results with the experimental data for C38 steel, so the mathematical model is considered as reliable.

The result of this validation is shown in Figure 51.8, in which the measured temperatures are compared with the simulation results. In particular, the red line represents the average value of the billet temperature (average of temperatures in centre and surface layer), as measured experimentally, while the blue line represents the simulated value of the average temperature of the billet (average of temperatures in the three layers).

It is evident that a certain mismatch exists between the experimental average temperature and the simulated one, probably due to actual thermal capacity and/or thermal resistance values different from the available ones.

In order to improve data matching between experimental and simulated average temperatures, an iterative procedure has been developed to "adjust" the thermal capacity value for each temperature, comparing the local derivative of the experimental average temperature with that of the simulated one. Figure 51.9 shows significant improvement obtained with such a correction.

Some inaccuracies still remain in the model, as evident in Figure 51.10, which compares the time history of the simulated temperatures of the three layers with the measured surface and internal temperatures: all the simulated temperature readings are between the two measured ones, and they are practically indistinguishable from one another.

This could be related to inadequate thermal resistance values, which do not correctly model the thermal energy flux between the layers. An iterative procedure, similar to the previous case, has been applied to correct them by comparing again the experimental average temperature with the new simulated ones. The results are reported in Figure 51.11, which show a quite satisfying matching of both the average and the external/internal values of the measured and simulated temperatures.

The relative errors between experimental and simulated average temperatures are shown in Figure 51.12.

This proves that the proposed model, with suitably amended data, is capable of providing a relative error below 2% in the thixoforming operating range of temperatures.

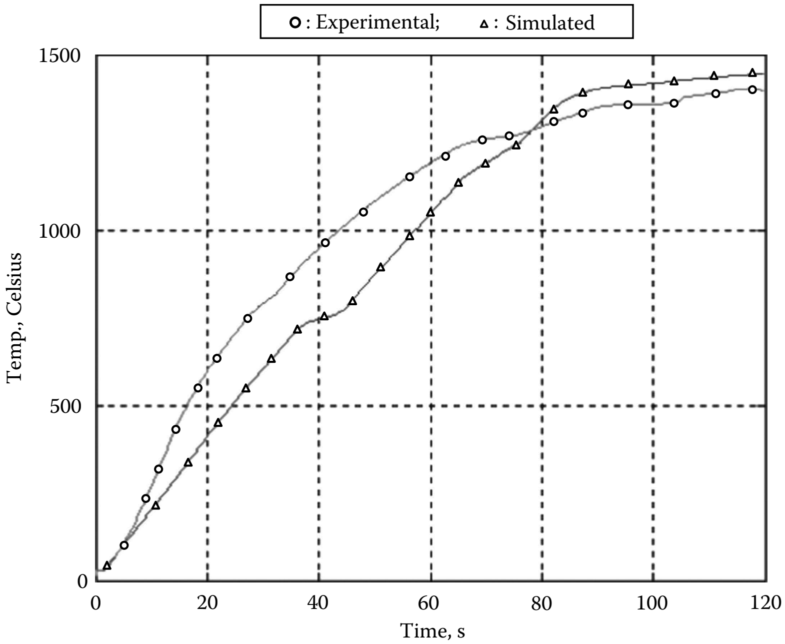


FIG. 51.8
Comparison of simulated and real temperature development.

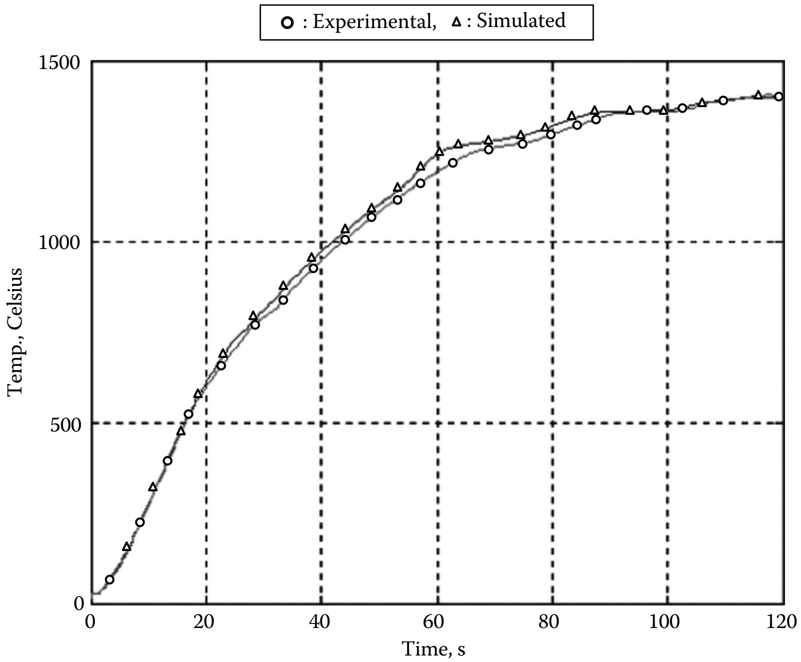


FIG. 51.9
Simulation results with corrections of the thermal capacity data.

The modified steel data used in the simulation model are shown in Figure 51.13.

The use of raw experimental data introduces mismatch between simulation and experiments. Therefore, an adaptive method has been developed to generate a correction factor depending on the temperature, on the electrical resistance, the thermal capacity and the thermal resistance. This method is mainly based on derivative of process temperature vs. time.

ONLINE ESTIMATION AND CONTROL OF THIXOFORMING PROCESS

From the model of the heating previously described, we developed a program for real-time estimation of temperature in order to use the model; we added also a suitable control feedback in order to reach automatically the desired temperature during the thixoforming process.

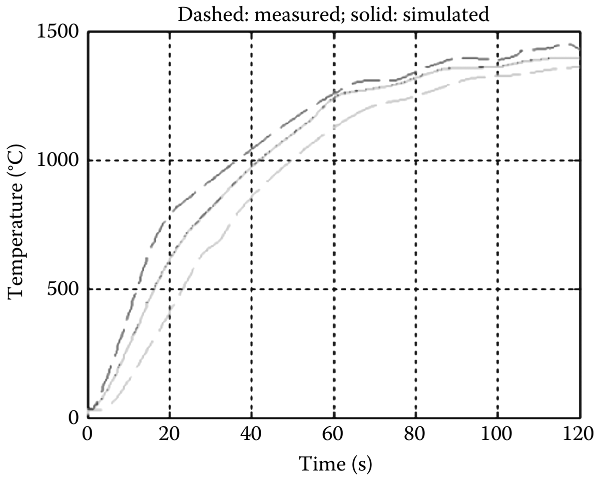


FIG. 51.10

Improved simulation of temperature development.

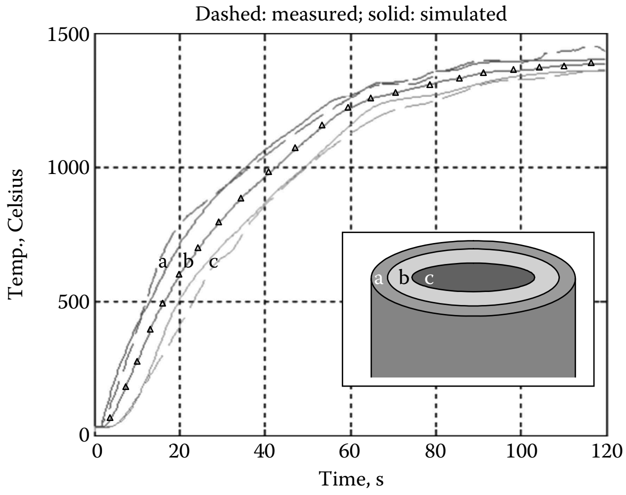


FIG. 51.11

Simulation results with corrections of the thermal capacity and resistance data.

Estimation

The control system was has been developed (Figure 51.14) for online estimation and control of thixoforging process. The model takes the power input *u* and provides billet temperature *T* as the output, computed according to the mathematical model described above. This model provides a reliable evaluation of the temperature for comparison with experimental results.

We evaluated the model outputs comparing them to that of pyrometer, and we noticed that the pyrometer estimations were more accurate than those of the model up to the thixoforging temperature range.

The model allows also the possibility to change the threshold temperature, according to user's choice, in order to switch automatically from the pyrometer temperature evaluations to the model. With this mixed procedure, it is possible to evaluate correctly the temperature in the whole range of interest.

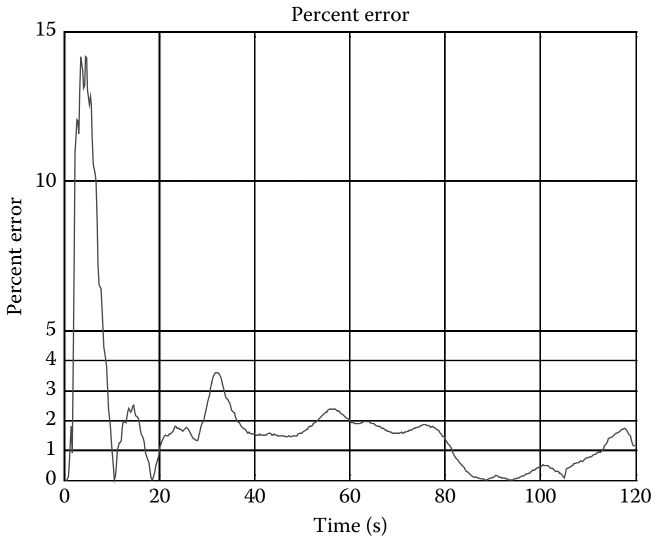


FIG. 51.12

Relative errors between calculated and measured temperature.

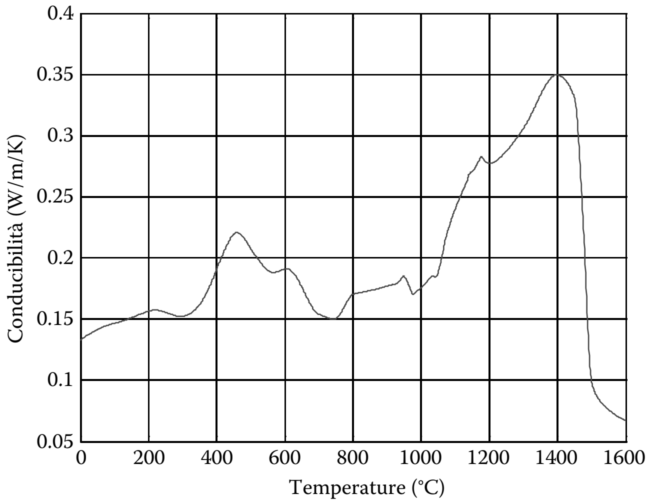


FIG. 51.13

Modified steel data: thermal conductivity.

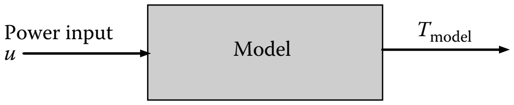


FIG. 51.14

Signal and information flow to estimate the billet temperature by means of a model-based heating system.

Control

Improvement is possible with feedback control system in order to reach a desired temperature automatically. PID design approach was selected for its convenience.

The control approach is sketched in Figure 51.15.

From the MATLAB model of the billet (Figure 51.16), a control system has been designed with the PID controller located at the feedback path.

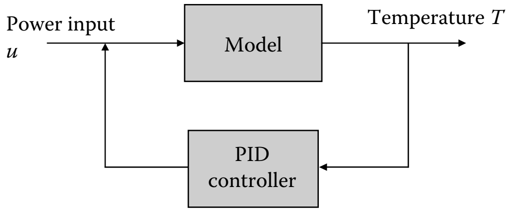


FIG. 51.15
The PID concept.

The values for *P*, *I*, and *D* are estimated after several experiments of the desired performances of the control, and are tuned with some runs of MATLAB/SIMULINK.

After the porting of MATLAB/SIMULINK source code for control feedback in Visual Basic, some other features are added in order to improve usability of a user program interface using WinSit shown in Figures 51.17 and 51.18.

The feedback control was tested with the pyrometer and the model, and the test runs were made both with plant for emulation (i.e., Windows PC with WinSit hardware and Software) with a real plant. The tests covered the following cases: open loop with model and open loop without model, and closed loop for set point temperature with and closed loop without model.

A screenshot of the latter is shown in Figure 51.19, where different set point temperatures were selected during the run times.

After a large amount of test runs, it was concluded that the control system worked properly according to the PID coefficients previously selected.

Physical Capability Support

With this feature, we add to user interface (WinSit) the capability to change geometrical and physical properties of the billet. Thermal resistance and capacitance are stored in files selectable by the user; these files are saved in configuration of WinSit.

Moreover, with this release, it is possible to change the billet properties directly from graphical interface. Figure 51.20 shows the new pop-up menu.

Hardware and Software Support

To obtain the above simulation results, the hardware architecture of standard machines has been modified as depicted in Figure 51.21. The system has the following characteristics:

1. Analog to frequency converter and frequency to digital converter sends data from field to industrial PC (Field → ANFOT → INTACQ → PC).
2. The software running on PC calculates and synthesizes power reference for the heating equipment, based on the real-time mathematical model of heating of the billet.
3. Power reference is translated from digital to analog and sent to the power source (PC → INTACQ → REG 2000 → COPOR → RECTIFIER BRIDGE → Field).

The system works in a closed loop form and in an adaptive way based on the real-time mathematical model of heating of the billet.

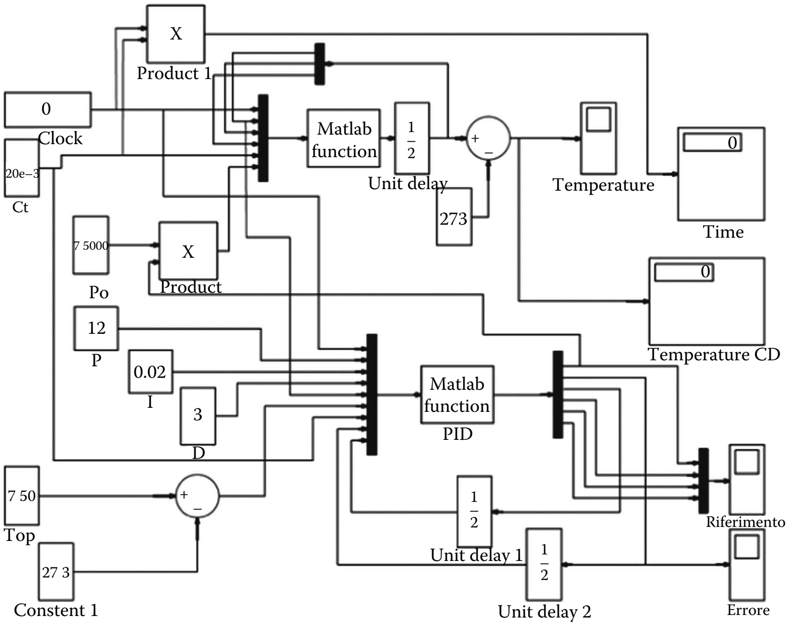
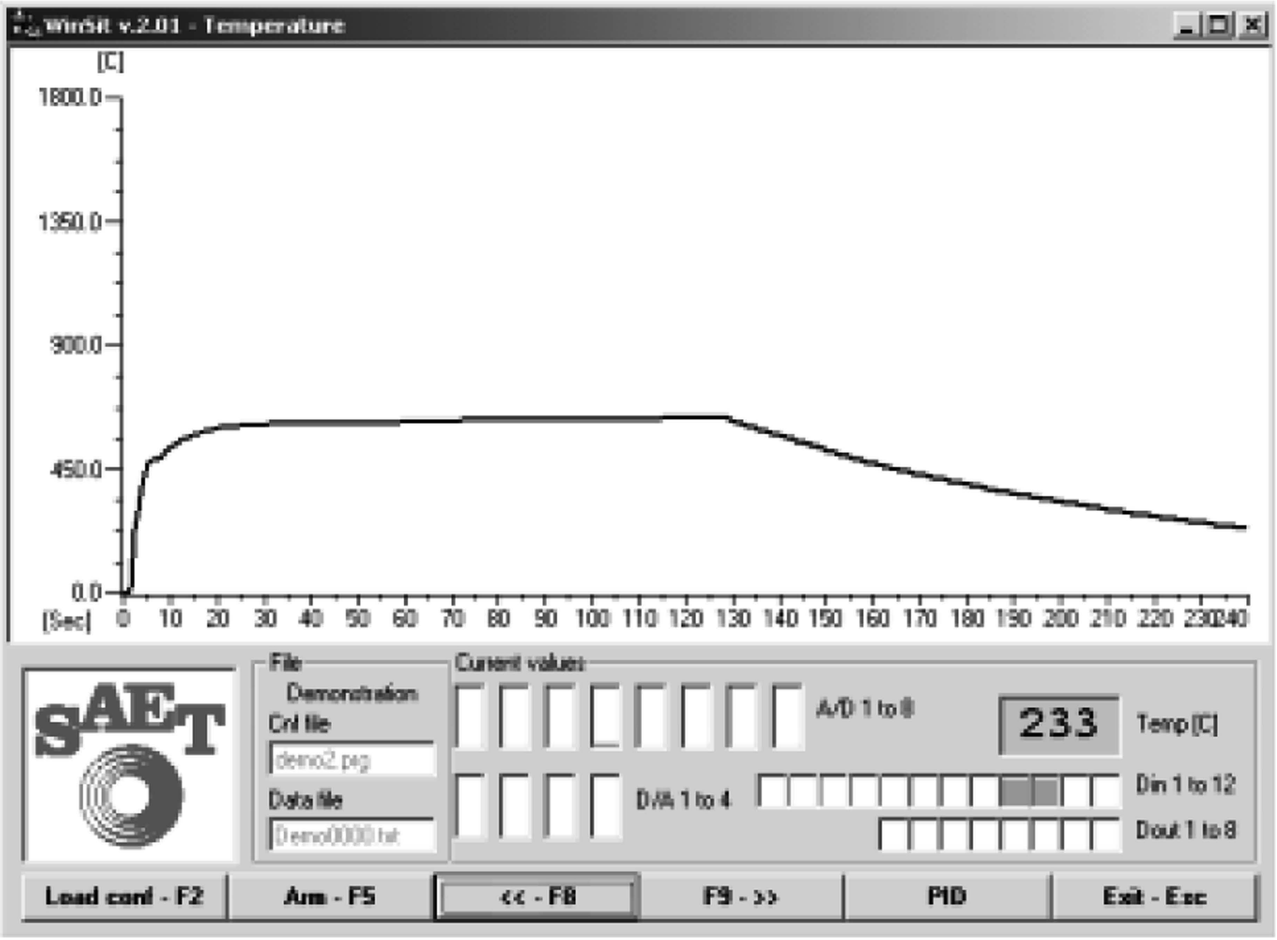


FIG. 51.16
The PID controller for temperature regulations.



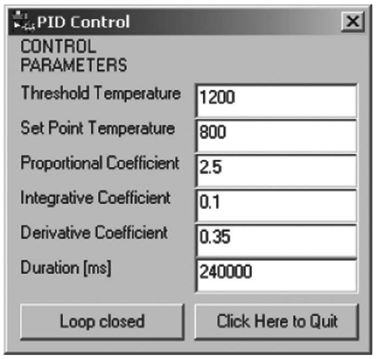
Demonstration

Crd file: demo2.pcg

Data file: Demo0000.txt

233 Temp [C]

FIG. 51.17
WinSit with PID application.



CONTROL PARAMETERS

Threshold Temperature: 1200
Set Point Temperature: 800
Proportional Coefficient: 2.5
Integrative Coefficient: 0.1
Derivative Coefficient: 0.35
Duration [ms]: 240000

FIG. 51.18
Pop-up menus for PID and temperature parameters.

The heating strategy is implemented and monitored by a user interface application (WinSit), which runs in real time on the PC depicted in the Figure 51.22.

The special control system WinSit allows to define the desired heating cycle and to check the electrical parameters during the entire heating process. The graphical user interface of the software was written in Visual Basic.

WinSit Software

WinSit provides three basic functions:

1. *Converter driving*: It drives the MF converter by sending the heating command (digital signal) and the power reference (analogical signal).
2. *Peripheral devices controlling*
   a. Converter
   b. Refrigerator pump
   c. Frequency change switches
3. *Measurements of electrical working parameters*: They check the electrical working parameters from the converter and, eventually, other two available analogue signals from the outer world.

FUZZY LOGIC CONTROL

An alternative method of experimentally obtaining optimized heating functions by using a fuzzy logic controller is introduced as an alternative method. Under steady-state

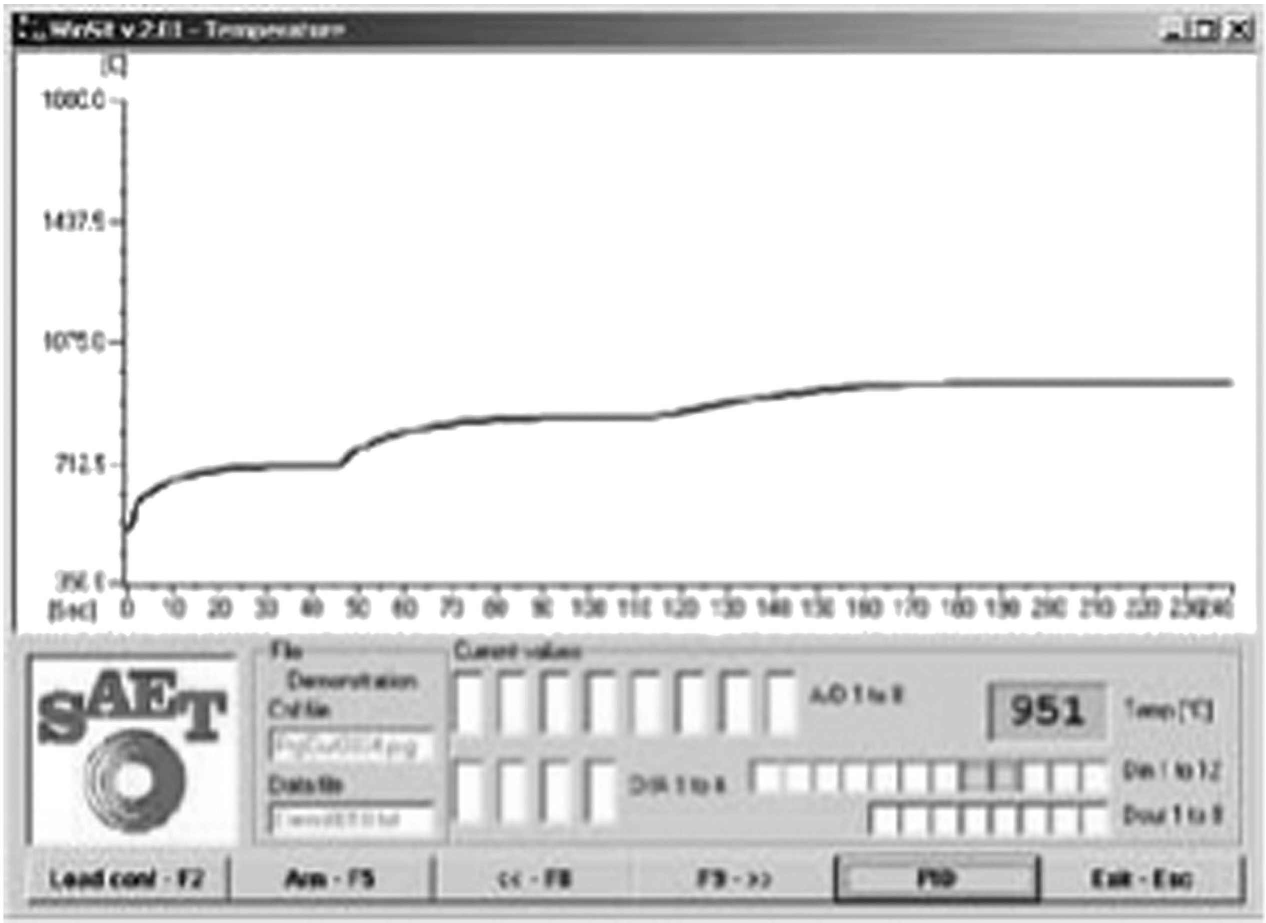
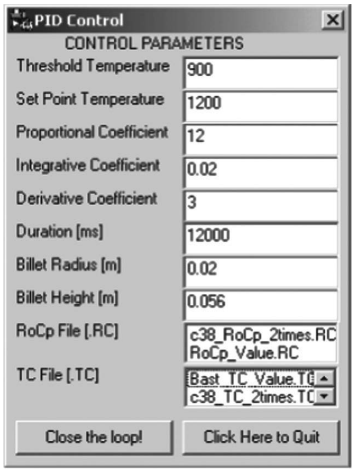


FIG. 51.19
Different set point temperatures.



CONTROL PARAMETERS

Threshold Temperature	900
Set Point Temperature	1200
Proportional Coefficient	12
Integrative Coefficient	0.02
Derivative Coefficient	3
Duration [ms]	12000
Billet Radius [m]	0.02
Billet Height [m]	0.056
RoCp File [.RC]	c38_RoCp_2times.RC RoCp_Value.RC
TC File [.TC]	Bast_TC_Value.TC c38_TC_2times.TC

FIG. 51.20
Improved pop-up menu.

environmental conditions, this method allows a quick and reproducible reheating. The main advantages of the fuzzy logic–based approach are that no specific material data is required, system specific properties such as the efficiency need not be explicitly determined, and that the practical implementation could be realized with minimum experimental work.

A fuzzy logic controller is used to obtain optimized time-dependent heating function *P*(*t*) for the induction heating of billets for thixoforming. Normally, such functions are once worked out in laboratory experiments and subsequently are transferred to series production processes. This is valid if the edge conditions in series production are the same as in the laboratory experiments. Once a heating cycle is validated, the heating of the billets in series production processes is carried out unsupervised without further monitoring of the temperature.

Generally fuzzy logic is a method suitable for transfer control problems, which could be expressed easily in colloquial terms in computers. In the case of induction heating, the control problem has been formulated as follows:

1. Heating the billet in the shortest time possible to process temperature, that is, "as much heating power as available" is needed.
2. At the end of the heating process, the billet must exhibit a homogenous temperature distribution.
3. If the difference between surface and core temperature is "too high," the heating power has to be reduced

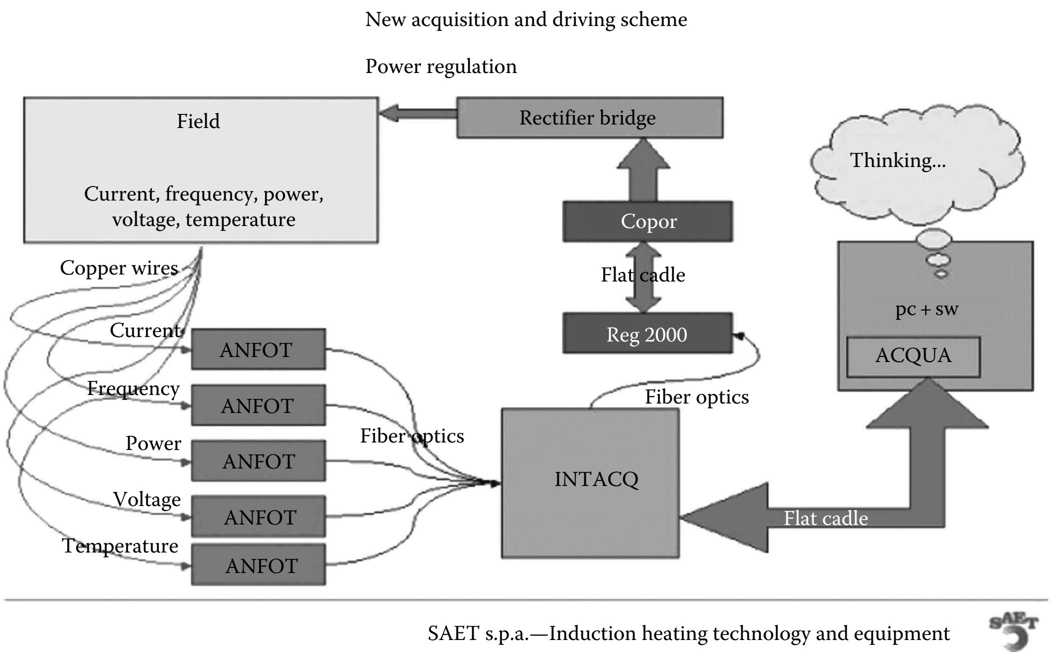


FIG. 51.21
The hardware architecture for controlling heating cycles.

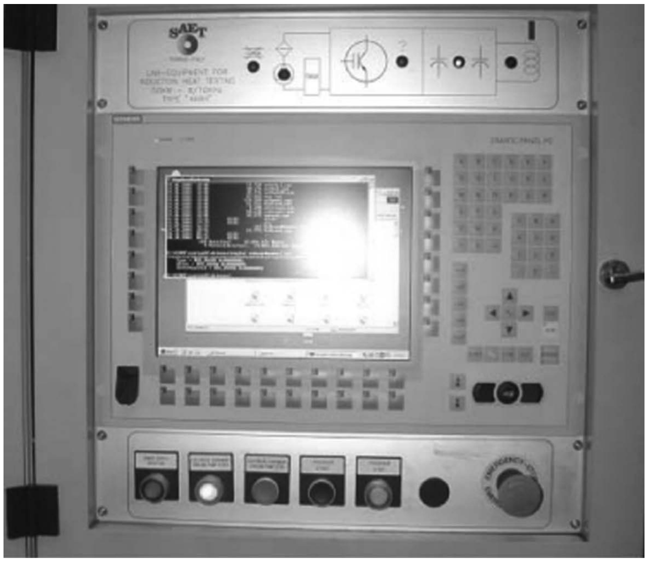


FIG. 51.22
User interface of inductive heating control.

"a little bit" in order to equalize the temperature in all areas of the billet by hat conduction.
4. The heating power should only be "slightly" reduced so that already stored thermal energy in the billet will not be lost by radiation.

The theory of fuzzy logic is basing on the theory of fuzzy sets that was introduced by Lofti Zadeh in 1965 at the University of Berkeley and it has found many industrial applications [4]. In automatic control engineering, fuzzy logic is used to impress one or more system output parameters as desired time-dependent variables. In the case of induction heating, these parameters are the surface and the core temperature of a billet. It is not possible to control these parameters directly but they can be affected by other variables like the converter frequency and the voltage.

With fuzzy logic, a control strategy is described directly without application of a mathematical model, for example, by observing a skilled machine operator. The knowledge base of a fuzzy logic controller contains control strategies analogous to the observations in terms of colloquially formulated rules. In the ideal case, the fuzzy controller is described completely by a set of such rules. The colloquially described ("linguistic") terms are in theory expressed by membership functions ("fuzzy sets"). These functions specify to which degree a certain property applies to an item. Fuzzy sets are usually defined by triangular- or trapezoidal-shaped functions (Figure 51.23).

The control variable has to be represented by a crisp number. For this, an additional step called "defuzzification" is necessary. Here the knowledge base contains two if–then rules. The controller uses in each case the minimum of the degrees of performance of the premise of each rule. By building the maximum of the particular resulting set, one single fuzzy set is derived. The crisp set value for the control variable is determined by building the centroid "defuzzification." This is done by determination of the centroid of the area of the membership function over the control variable. This method is known as "MIN-MAX-Inference." For more theoretical treatment of fuzzy control, refer to Chapter 14.

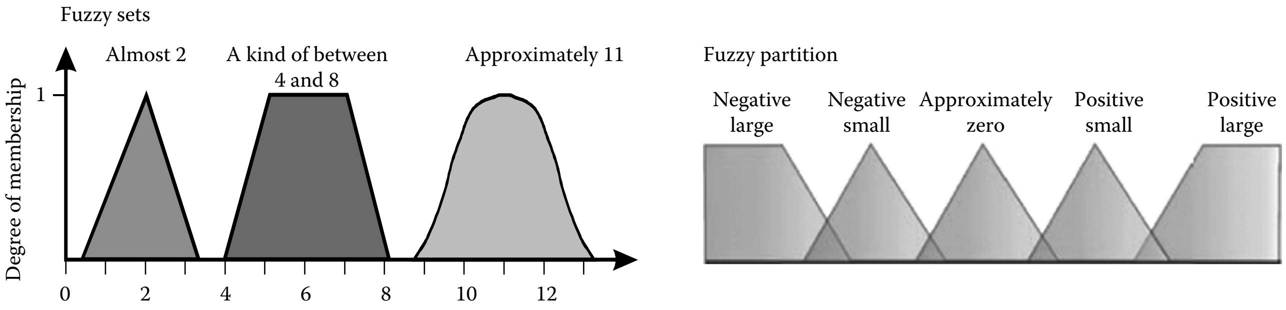


FIG. 51.23

Left: Examples for subjective and context depending values represented by fuzzy sets. Right: Fuzzy segmentation of a value range of a variable with floating transitions between the partitions.

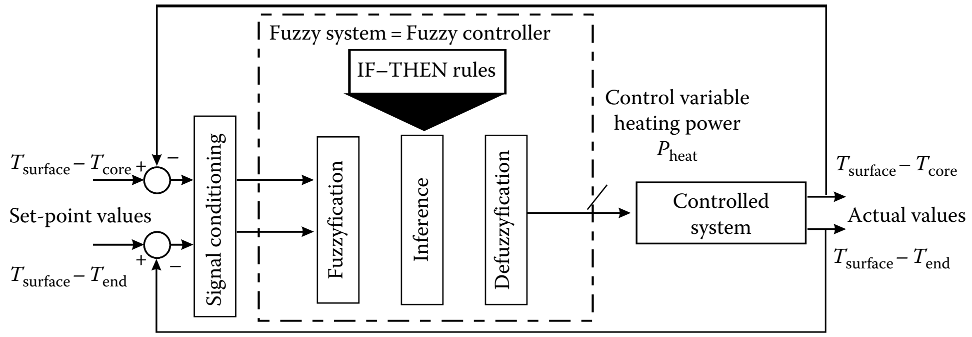


FIG. 51.24

Block diagram of the applied fuzzy controller.

Design of the Fuzzy Controller for Inductive Heating of Steel Billets

The block diagram (Figure 51.24) of fuzzy controller and its input and output parameters applied in this study are described in six steps as follows:

1. Definition of the input and output variables of the controller as
   Inputs: $\Delta T = T_{surface} - T_{surface,end}$ and $\Delta T_{sc} = T_{surface} - T_{core}$
   Output: P_{heat}.
2. Specification of variables domains as
   ΔT_{sc}: −25 to 500 K, ΔT: −1400 to 50 K, and P_{heat}: 3–11 (no dimension).

TABLE 51.1

Knowledge Base of the Fuzzy Controller for the Induction Heating of Steel Billets

Heating Power (Set Point)		ΔT_{sc}			
		Small	*Medium*	*Large*	*Very Large*
ΔT	Far	Very high	Very high	Very high	Very high
	Near	Low	Medium	High	High
	Goal	Very low	Low	Medium	Medium
	Too far	Very low	Very low	Very low	Very low

3. Definition of linguistic terms and fuzzy sets: In Figure 51.25, a graphical representation of the fuzzy sets is given. The requirement of overlapping domains of the used variables is fulfilled.
4. Creation of the knowledge base of the fuzzy controller: It has to be ensured that the working range of the controller is completely covered by If–Then rules. Otherwise the behavior of the controller would be partly undefined. The knowledge base is defined as given in Table 51.1. The following example illustrates the function of the knowledge base of the controller.

   IF $\Delta T_{sc} = \textit{small}$ AND $\Delta T = \textit{far}$ THEN $P_{heat} = \textit{very high}$

   The triangular membership functions are overlapping to 50% and the knowledge base is built so that maximal two rules could be active at the same time.
5. Application of the inference machine (operators, inference, data type, and defuzzification):
   a. The inference method is the MAX–MIN inference as described above.
   b. Defuzzification is performed by determination of the centroid as described above.
6. Optimization of the controller: The optimization is mainly done by modification of the membership functions and only in exceptional cases by adding

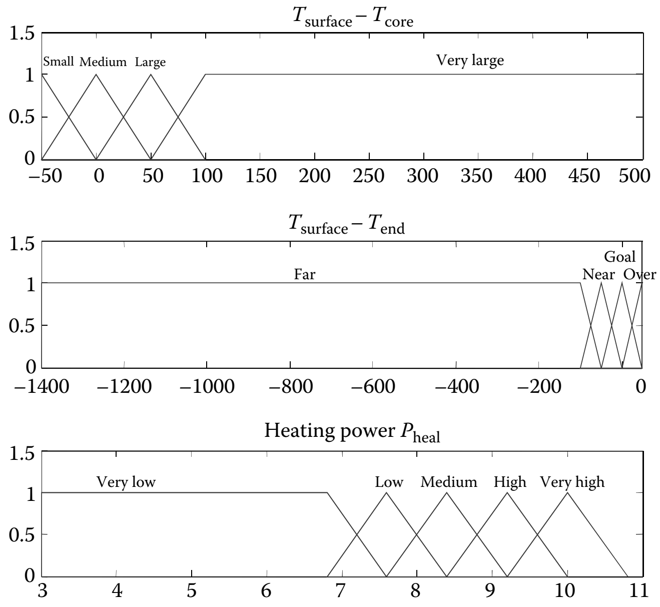


FIG. 51.25

Used fuzzy sets for controlling the induction heating of steel billets.

or modifying particular If–Then rules. In the present case of induction heating for the production of SKL flanges, the heating cycle is divided into two phases:

a. Phase 1: quick heating up to $T_{surface} \approx 1300°C$ with $P_{heat} = \mathit{Maximum}$
b. Phase 2: fuzzy controlled heating up to $T_{surface} = T_{set} = 1440°C$ with $\Delta T_{sc} \leq 10\,K$

Phase 1 has the purpose to increase the billet's enthalpy very fast whereas the aspect of homogeneous temperature distribution is unimportant. Phase 2 is dedicated to an equalization of temperature in the billet as well as to finally reaching the desired process temperature. Moreover, phase 2 should also be kept as short as possible and the temperature must also not exceed the set point value because this may lead to unwanted partial or complete melting of the billet.

In phase 2, the radiation loss must be compensated by induction heating. Since the actual temperature would have probably not yet reached its set point value, the provided heating power has to be high enough to ensure a further gain of enthalpy. In this example, the input values are $\Delta T_{sc} = 5\,K$ and $\Delta T = -75\,K$. The resulting heating power has the set point value 9.6. This value equals 96% of the available maximum power.

Results of Fuzzy-Controlled Heating Process

By application of the described fuzzy logic controller, several cylindrical billets (Ø30 × 59 mm) were heated up to process temperature. The reference for an optimized heating cycle was a previously generated heating curve that was determined by finate element analysis (FEA) simulation with subsequent manual iteration loops. The result is shown in Figure 51.26.

The heating curve obtained with fuzzy control is shown in Figure 51.27. The set point of the temperature was $T_{surface} = 1400°C$ and the maximal tolerated difference between core and surface temperature was $\Delta T_{sc} \leq 20\,K$. After a heating duration of $t = 41\,s$, these demands were very well fulfilled ($\Delta T_{sc} = 20\,K$). With the FEA-based approach $T_{surface} = 1438°C$ was reached in $t = 45\,s$, whereas the temperature difference between core and surface was $\Delta T_{sc} = 38.2\,K$.

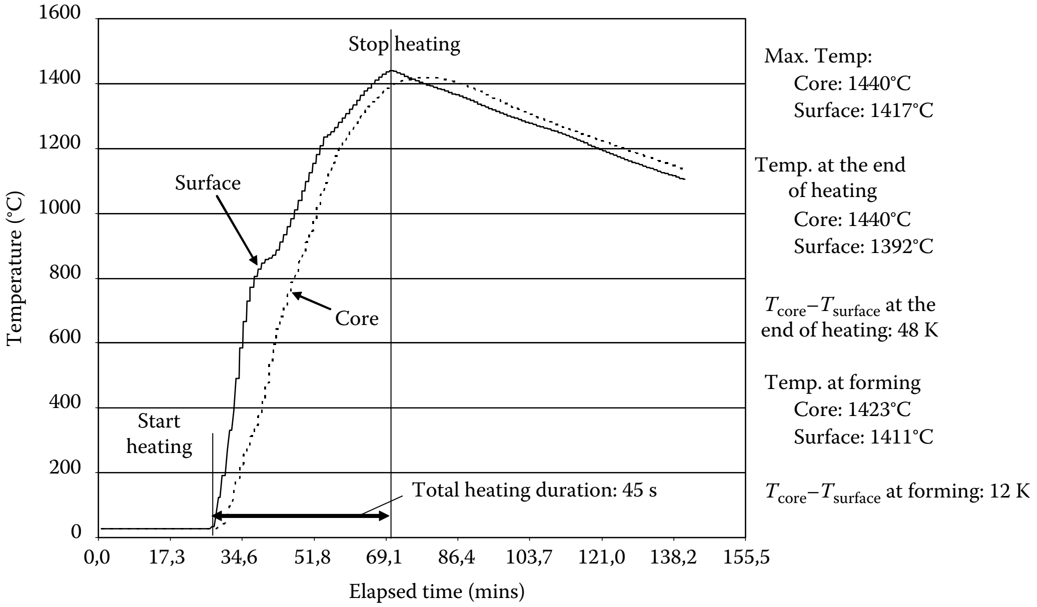


FIG. 51.26

Reference temperature evolution obtained by using a FEA optimized heating cycle.

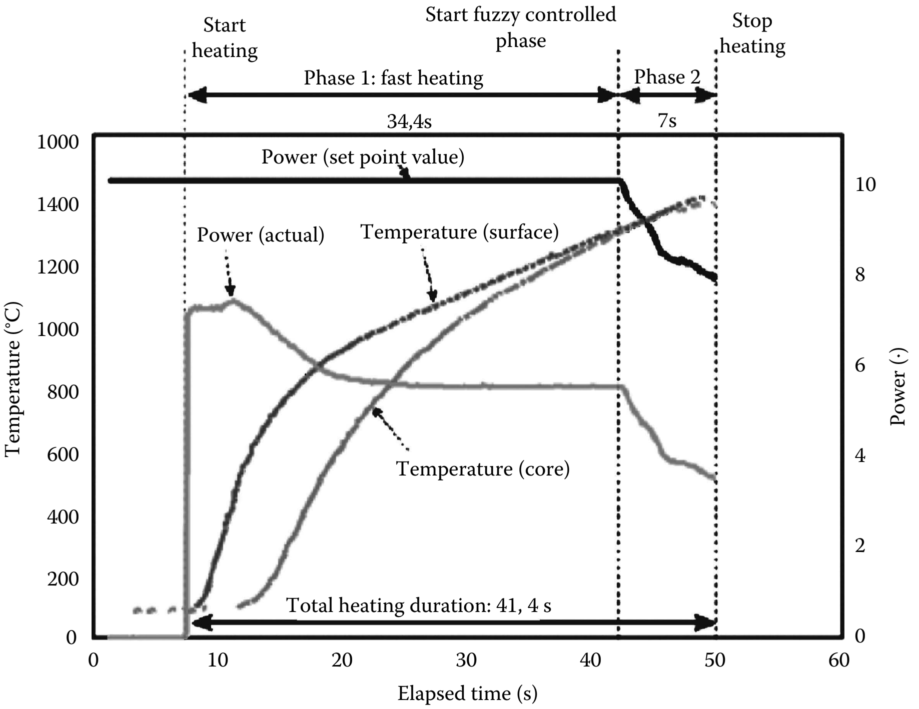


FIG. 51.27
Fuzzy logic optimized heating of steel billets for the production.

AUTOMATION OF THE PROCESS

Because the process window for thixoforming is about 30–50 K at a temperature level of about 1400°C it is mandatory to automate the complete production process in order to ensure a reliable and reproducible process parameters. For this purpose, a handling system was developed that transfers the hot billets completely automatically into the die. The process steps, heating, billet transfer, and forming are all linked together and are controlled by an adapted software running on a master PC. When the heating cycle is finished, a “READY” signal is send from the local heating control to the process computer, which controls all steps of the handling action. After a successful transfer, it launches the local process PLC of the hydraulic press and the forming action will be performed. The control of the press is implemented locally on the press hardware. Besides the synchronization of special tasks, the master PC is also responsible for acquisition of process data, detection of faults, and emergency reactions. It offers also a convenient user interface that allows manual access to every single action the system could ever perform and is, thus, a powerful tool for setting up the production line or its adaptation to other parts or tools.

Mechanical Setup

Figure 51.28 shows the handling system for the fully automated production of thixoformed steel parts. The ingoing billets are stored in a tubular magazine and will be separated from each other and transferred by means of a slider bar. A horizontal gripper transfer is used for storing and moving ceramic cylinders. At the beginning of the production cycle, a billet is placed on the leftmost ceramic plate and then pushed vertically into heating position by a pneumatic cylinder. After reaching the heating position, the control is handled over to the subsystem “inductive heating” and the billet is heated up to process temperature. Immediately after

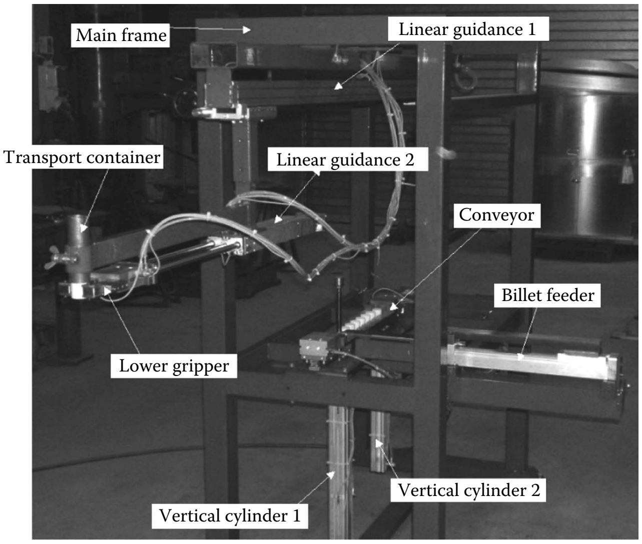


FIG. 51.28
Handling unit—general setup.

finishing the heating, the hot billet to be pushed into a transport container and transported to the press.

At the beginning of the thixoforming cycle, the first plate in the row as shown in this figure is put onto the vertical cylinder 1. After that a steel billet is moved from the billet storage onto the ceramic plate. Vertical cylinder 1 lifts the ceramic plate with the billet on it into heating. Because of the selected thickness of the ceramic plate vertical cylinder 1 will not be affected by the magnetic field. At the end of the heating cycle, vertical cylinder 1 lifts plate and billet into the transport container where the lower gripper grips the ceramic plate. The billet is now inside the transport container, which could be flushed with inert gas in order to provide an effective mean against scaling. By means of linear guidance 1, the whole unit consisting of transport container, lower gripper and linear guidance 2 is immediately moved towards the forming tool. After reaching the foremost position linear guidance 2 moves backward and the hot billet is dropped into the forming tool. After that, linear guidance 1 moves back again. The ceramic plate can now be moved down again by vertical cylinder 2 and the whole row of plates will be moved one step further so that the next cycle could be released.

All movements in the handling system are made by means of pneumatic drives. This concept allows a simple and versatile process control in connection with rapid movements for handling of ceramic plate and steel billet. In the experiments, a handling time of the steel billet from end of heating cycle until the release of the press stamp to begin thixoforming of only 3.1 s was attained. The movement of the pneumatic drives especially due to acceleration and deceleration has to be characterized as "rough." For a smoother handling, the handling time is increased to 3.3 s in order to reduce vibrations.

Although the handling systems performed quite well from the beginning, there was one critical point that needed intensive re-working. After heating stop vertical cylinder 1 has to move the heated billets into the transport container. At this point of the process, the billet often crashed against the wall of the container instead of going in. However, the container provides enough space for the billet and was well aligned to the upward moving billet this kind of malfunction occurred frequently. To overcome this obstacle the following mechanical measures were made:

- Provision of a funnel to align the part when moving upward
- Provision of a modified gripper design (lower gripper) that acts also as a "funnel"
- Provision of a redesigned transport container

The first two of the described measures were not sufficient to fix the problem completely. However, the occurrence of malfunctions was decreased significantly. For this reason, a modified design of the transport container was worked out as shown in Figure 51.29. The container itself is still cylindrical. This is important because when it is opened by removing the ceramic plate, the billet has to touch the wall of the container, which acts as a guidance when it is falling down into the tool. By means of sheet metal, a funnel-shaped insert was formed that rectifies the billet when it is pushed upward by vertical cylinder 1. This setup allows a good function of the handling device because the inner diameter of the transport container is big enough in any case and the position of the billet in the container is always assured through the "funnel" insert. In practical use, this designed proved its reliability.

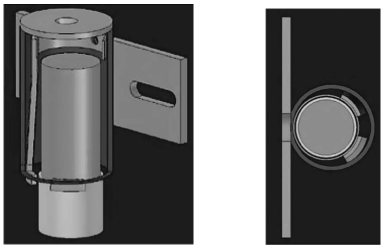

Sectional view Top view

FIG. 51.29
Transport containers.

CONCLUSIONS

We have developed two main methods for a sophisticated inspection system for the temperature measurements and the adjustment of the heating parameters. The development and implementation of the control system for inductive heating of steel billets is accomplished according to the production needs, the model for the billet is ported into a real-time environment for industrial application, and a control feedback is added to reach the desired temperature. Furthermore, in order to extend the capability of the tool for different steels, physical properties inside user program (i.e., geometrical ratio, thermal capacity, and thermal conductivity) are made modifiable by users.

The fuzzy logic, as an alternative approach, delivers comparable results to the FEA-based optimization of heating cycles. Its main advantage lies in the reduced necessary experimental and simulation work and that no thermophysical material data is necessary.

The studies for energy control of a billet carried in this work could be extended for further applications, beyond thixoforming.

Acknowledgments

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